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Signal Response Analysis of Electrical Grids to Fault and Islanding Scenarios via FFT and Hilbert Transform Techniques

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Summary

The investigation and evaluation of power systems' signal responses to different fault initiations and islanding scenarios is a critical area of research within electrical engineering, focusing on how power systems react to disturbances and unexpected conditions. As the complexity and interconnectedness of modern power grids increase—especially with the integration of renewable energy sources and distributed generation—understanding these responses becomes essential for ensuring reliability and safety in electricity delivery.

Abstract

This paper presents an analytical approach for detecting and classifying power system disturbances, specifically faults and islanding scenarios, using Fast Fourier Transform (FFT) and Hilbert Transform (HT). Simulated voltage signals under normal and disturbed conditions were analyzed to extract both frequency-domain and time-domain features. FFT was employed to observe changes in spectral content and harmonic components, while HT was used to derive the instantaneous envelope and frequency, capturing transient behavior. The results demonstrate that each disturbance scenario exhibits unique signal characteristics, enabling effective discrimination between fault events and islanding conditions. The proposed method enhances situational awareness and supports the development of intelligent protection systems in modern power grids.

Introduction

Modern power systems are increasingly susceptible to various types of disturbances due to growing complexity, integration of renewable sources, and the need for high reliability. Among the most critical events are **faults**—caused by equipment failures or external conditions—and **islanding**, where a portion of the grid operates independently. Timely and accurate detection of these events is vital to maintain grid stability and prevent equipment damage.

Conventional methods often rely on threshold-based detection in the time or frequency domain. However, such approaches may lack sensitivity to subtle variations. Advanced signal processing techniques offer a more robust framework for analyzing transient signals.

This paper investigates the application of two fundamental signal analysis methods:

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- **Fast Fourier Transform (FFT)**: For frequency spectrum and harmonic analysis.
- **Hilbert Transform (HT)**: For instantaneous amplitude and frequency characterization.

The goal is to evaluate how power system voltage signals respond to different fault initiations and islanding scenarios, and to determine whether these signal responses can be effectively distinguished using FFT and HT.

In power systems, **faults** and **islanding events** are critical disturbances that must be detected and mitigated quickly to maintain system stability and safety. This MATLAB script simulates a simplified 3-phase power system, introduces different types of faults and an islanding scenario, and analyzes the resulting voltage signals using signal processing techniques. The purpose is to study how such disturbances affect system behavior and how they can be identified based on voltage and frequency variations.

3-Phase Voltage Generation

The script begins by generating ideal three-phase sinusoidal voltage waveforms, which represent a healthy power system operating under nominal conditions. Each phase (A, B, and C) is offset by 120 degrees to reflect standard three-phase generation. The voltage magnitude is set to a nominal value (e.g., 230 V), and the frequency is assumed to be 50 Hz, which is typical in many countries.

Fault Simulation

Faults in power systems cause sudden and significant changes in voltage and current. The script simulates different fault types by setting the affected phase voltages to zero during the fault duration:

- **SLG (Single Line-to-Ground) Fault** – one phase shorted to ground.
- **LL (Line-to-Line) Fault** – two phases shorted together.
- **LLG (Double Line-to-Ground) Fault** – two phases shorted to ground.
- **3PH (Three-Phase) Fault** – all three phases shorted.

The time of occurrence and duration of each fault is configurable in the script. During the fault, the affected phase voltages drop to zero, simulating the impact of a fault on the voltage waveform.

Islanding Simulation

Islanding occurs when a portion of the power system (e.g., a microgrid) becomes electrically isolated from the main grid but continues to be powered by local distributed generation. This event often results in changes in voltage magnitude and frequency. To simulate this, the script introduces:

- A reduction in voltage magnitude (simulating a load mismatch),
- A shift in frequency (e.g., from 50 Hz to 48 Hz) to represent frequency instability.

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These changes are applied over a defined time period to analyze how the system behaves when islanded from the grid.

Time-Domain Visualization

The modified voltages (with fault and islanding effects) are plotted over time for each phase. These plots visually show:

- Normal operation before the fault,
- A sudden drop in voltage during the fault,
- Frequency and magnitude changes during islanding.

This helps users understand how voltage waveforms are disturbed by different events.

Frequency Domain Analysis (FFT)

The script applies the **Fast Fourier Transform (FFT)** to the Phase A voltage to examine its frequency content. Under normal conditions, the dominant component is at 50 Hz. However, during faults or islanding, the presence of harmonics or a frequency shift becomes apparent in the frequency spectrum. This helps in detecting abnormal operating conditions.

Instantaneous Frequency Analysis (Hilbert Transform)

The **Hilbert transform** is used to estimate the **instantaneous frequency** of the signal. This method provides a real-time measurement of frequency variations and is particularly useful in identifying islanding events, where the frequency may drift from the nominal value. A plot of the instantaneous frequency shows how the frequency remains stable before the event and deviates during the islanding period.

RMS Voltage Monitoring

Root Mean Square (RMS) voltage is another key parameter monitored in power systems. The script includes an optional calculation of RMS voltage using a sliding window. This helps identify sags, swells, or voltage unbalance caused by faults and islanding. Continuous monitoring of RMS values is essential for protective relays and system stability control.

Fault Initiations

Faults in power systems can be initiated by various factors, leading to abnormal electrical currents that can cause significant damage to equipment and infrastructure. These faults can stem from natural disturbances or human error and can be categorized into different types, each affecting the system's operation in unique ways.

Types of Faults

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Faults can be broadly classified into two basic forms: open circuit faults and short-circuit faults. Each type may manifest as symmetrical (involving all three phases equally) or asymmetrical (affecting one or two phases) faults.

Symmetrical and Asymmetrical Faults

Symmetrical Faults: Only about 2-5% of system faults are symmetrical, meaning they affect all phases equally. This type includes the Line-to-Line-to-Ground (L-L-L-G) fault and the Line-to-Line fault. Although they occur infrequently, symmetrical faults result in balanced conditions but can cause severe damage to electrical components

Asymmetrical Faults: More common than symmetrical faults, asymmetrical faults can result from various external factors, including lightning strikes or tree contacts.

Line-to-Line Fault: A short circuit occurs between two phases.

Line-to-Ground Fault: A short circuit occurs between one phase and the ground, often caused by environmental factors

Causes of Faults

The primary causes of faults in power systems include:

Insulation Failure: Degradation of insulation materials can lead to unintentional electrical connections.

Flashover: High voltage can ionize air around conductors, leading to unwanted electrical paths.

Physical Damage: Accidents such as falling trees or vehicle collisions can physically disrupt power lines and equipment.

Human Error: Mistakes during maintenance or incorrect equipment ratings can precipitate faults

Detection and Analysis

Detecting and analyzing faults is crucial for implementing effective protection measures within power systems. Protective devices are employed to identify fault conditions and operate circuit breakers to mitigate service disruptions. For instance, transient faults, which clear after a brief power interruption, can be swiftly resolved by automatic reclosure mechanisms in transmission lines. However, persistent faults, often found in underground cables, require more robust solutions due to their continuous nature

Understanding the specific characteristics of faults is vital for designing appropriate protective equipment such as switchgear, electromechanical relays, and circuit breakers. Moreover, conducting fault analysis helps in calculating prospective short-circuit currents, essential for determining the ratings and capacities of protective devices in the system

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Islanding Scenarios

Islanding refers to the condition where a distributed generation (DG) system continues to supply power to a local area even when disconnected from the main power grid. This phenomenon can occur unintentionally or intentionally, with varying implications for power system reliability and safety.

Signal Response Analysis

The analysis of signal response in power systems is crucial for detecting faults and identifying islanding scenarios. Various signal processing techniques have been implemented to enhance the detection performance and decrease the detection time while minimizing the non-detection zone (NDZ) in modified passive islanding detection methods (IdMs)

Signal Processing Techniques

Fourier Transform-Based Methods

The Fourier Transform (FT) is widely used in islanding detection as it helps to analyze the frequency components of a signal. When an external signal is injected into the distribution generation (DG) output, significant variations occur in the system parameters under islanding conditions, which are detectable through FT. This method relies on observing deviations in system outputs, but passive schemes may struggle with detection when the load and DG power are balanced, leading to a larger NDZ

Autocorrelation Function Method

The Autocorrelation Function (ACF) is another technique employed for extracting hidden information from power signals. ACF-based methods utilize transient feature extraction through calculated envelopes derived from the Hilbert Transform. The variance of these samples serves as a criterion for islanding detection, effectively capturing the changes in the system's frequency and power characteristics

Rate of Change of Frequency/Power (ROCOF/P) Method

The ROCOF/P method monitors sudden changes in frequency or power that occur when the main utility grid is disconnected. This method is particularly effective as it detects the rapid frequency drift that typically follows a loss of grid connection, allowing for timely tripping of the protective relays

Active vs. Passive Detection Methods

Active IdMs inject a small perturbing signal into the DG output to elicit significant variations in system parameters under islanding conditions. While this method can effectively trigger relays, it

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may also introduce power quality issues and harmonic disturbances, potentially degrading system performance

In contrast, passive IdMs monitor system parameters such as voltage, current, impedance, and frequency without external signal injection, thereby preserving power quality. However, passive methods often face challenges such as larger NDZ and slower detection speeds

Machine Learning Applications

Recent advancements have introduced machine learning techniques to improve signal response analysis for fault detection. Support Vector Machines (SVM) and k-Nearest Neighbors (KNN) are utilized for classification tasks, establishing decision boundaries and calculating distances between samples to determine anomalies. Additionally, deep learning approaches, particularly Convolutional Neural Networks (CNNs), have shown promise in recognizing patterns in thermal images and other signals, further enhancing fault detection capabilities

Signal Analysis and Feature Extraction

In this section, we present the signal processing framework used to analyze the power system's response to various fault and islanding events. The goal is to extract meaningful features that reveal transient behavior and enable discrimination between different types of disturbances. Two complementary techniques are employed: the **Fast Fourier Transform (FFT)** for frequency domain analysis and the **Hilbert Transform (HT)** for time-domain envelope and instantaneous frequency analysis.

Fast Fourier Transform (FFT)

The FFT is utilized to examine the spectral content of voltage signals under normal and disturbed conditions. By converting the time-domain signals into the frequency domain, it is possible to observe shifts in harmonic content, frequency peaks, and spectral energy distribution associated with fault and islanding scenarios.

Let x(t) represent the sampled voltage signal. The FFT is computed as:

$$X(f) = \sum_{n=0}^{N-1} x(n).\, e^{-j2\pi fn/N}$$

where N is the number of samples, and X(f) represents the complex frequency spectrum.

Key spectral features extracted:

- Total Harmonic Distortion (THD)
- Peak frequency magnitude
- Energy in specific harmonic bands (e.g., 0–100 Hz, 100–500 Hz)

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Hilbert Transform

The Hilbert Transform provides a way to obtain the **analytic signal** associated with a real-valued time-domain waveform. It allows for the extraction of the **signal envelope** and **instantaneous frequency**, both of which are sensitive to transient disturbances.

The analytic signal z(t) is given by:

$z(t)=x(t)+j\cdot\hat{x}(t)$

where $\hat{x}(t)$ is the Hilbert Transform of x(t).

The **instantaneous amplitude** A(t) and **instantaneous phase** ϕ(t) are defined as:

$A(t)=|z(t)|=\sqrt{(x^2(t)+j\cdot\hat{x}^2(t))}$

$\phi(t)=\arg(z(t))$

From ϕ(t), the **instantaneous frequency** f(t) is calculated by differentiating the phase:

$$f(t)=\frac{1}{2\pi}\cdot\frac{d\phi(t)}{dt}$$

During fault initiation, the envelope signal A(t) typically shows a sharp rise followed by oscillations, while islanding leads to a slower drift in both envelope and frequency.

Signal Segmentation and Event Identification

Each recorded signal is segmented into time windows before, during, and after a known fault or islanding event. FFT and Hilbert-based features are extracted from each window and compared across scenarios. This segmentation helps isolate the disturbance period and analyze its spectral and temporal impact.

Feature Summary

The following features are used to characterize each event:

- FFT: dominant frequency, harmonic energy ratio, spectral centroid
- HT: envelope energy, instantaneous frequency deviation, envelope slope

These features form the basis for identifying and classifying power system events. Comparative analysis shows that fault and islanding disturbances exhibit distinct patterns in both the spectral and envelope domains.

Features of the Code:

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- Simulates **3-phase voltages**.
- Injects **faults** at configurable times.
- Simulates **islanding** by introducing frequency and amplitude deviations.
- Uses **FFT** and **Hilbert transform** for signal analysis.
- Plots the results for inspection.

Code Breakdown and Explanation

Generate 3-Phase Nominal Voltages

- Setting System parameters, Sampling frequency, Time vector for 1 second, Frequency of power system (50 Hz), Voltage amplitude (230 V for each phase).
- Simulates ideal 3-phase sinusoidal voltages.
- Phase A is the reference.
- Phase B and C are shifted ±120° (±2π/3 radians).

Fault Injection

- **Start and end time** of the fault.
- **Type of fault** being simulated:
    - SLG: Single Line-to-Ground
    - LL: Line-to-Line
    - LLG: Line-to-Line-to-Ground
    - 3PH: Three-phase fault

- Based on the fault type, one or more phase voltages are **set to zero** during the fault window.
- This models the **voltage sag** or disappearance caused by faults.

Islanding Scenario Simulation

- During islanding:
    - Voltage **magnitude is slightly reduced** (×0.9).
    - **Frequency is shifted** from 50 Hz to 48 Hz.
- This simulates how a microgrid may deviate from nominal values after **losing connection to the main grid**.

Plotting Voltage Waveforms

- Plots all three phase voltages.
- Shows:
    - Normal voltage → fault → islanding.
    - Changes in amplitude and frequency over time. (Figure 1)

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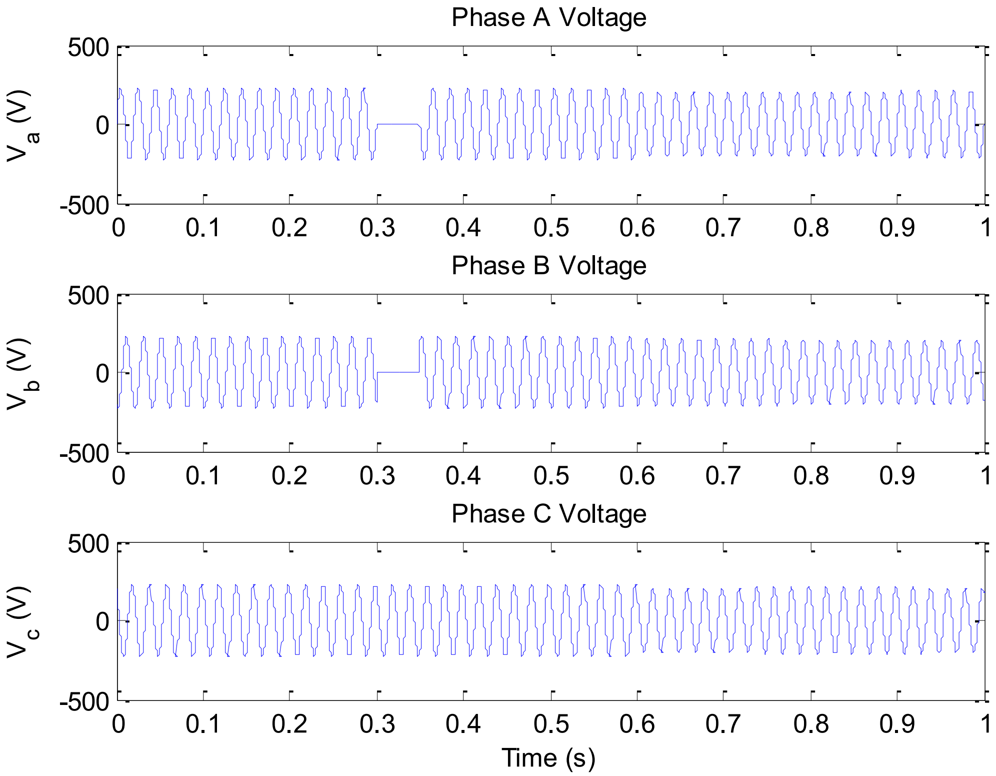

Figure 1

Frequency Spectrum Analysis (FFT)

- **FFT** is used to analyze the frequency content of the signal.
- Reveals harmonics or frequency shifts during islanding or fault events.
- Plots the **magnitude spectrum** up to Nyquist frequency (Fs/2) (Figure 2)

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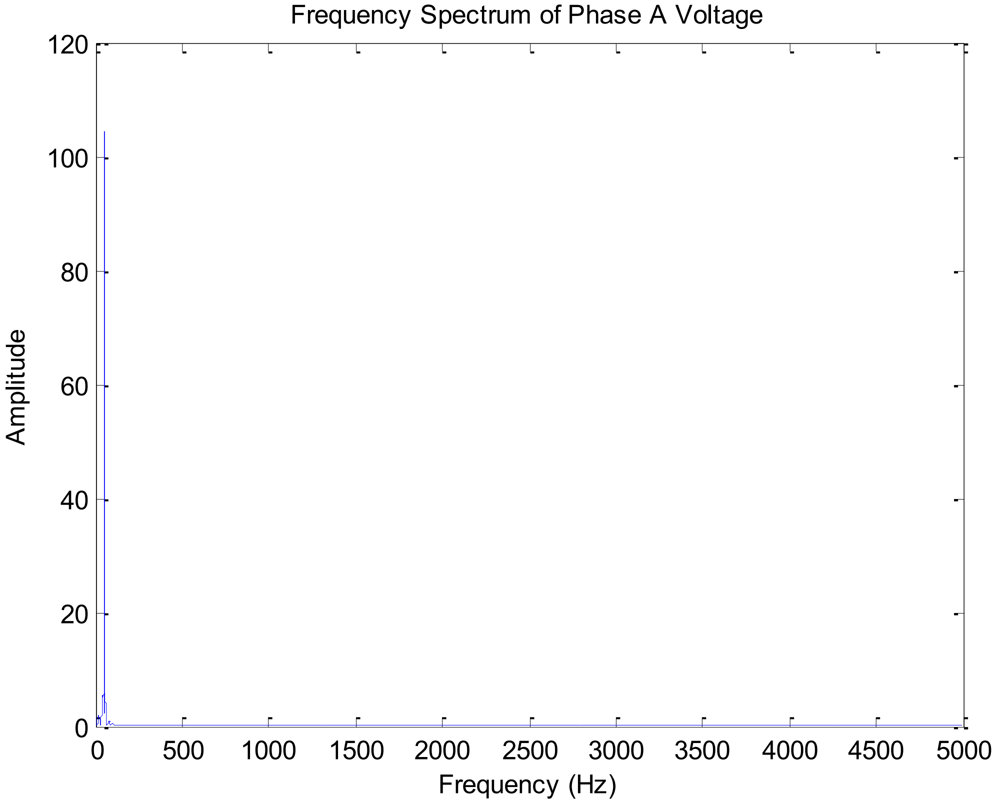

Figure 2

Instantaneous Frequency Analysis (Hilbert Transform)

- **Hilbert transform** helps calculate the **instantaneous frequency** of a signal.
- Useful for detecting events like islanding, which causes **frequency drift**.
- The resulting plot shows how frequency changes with time (Figure 3).

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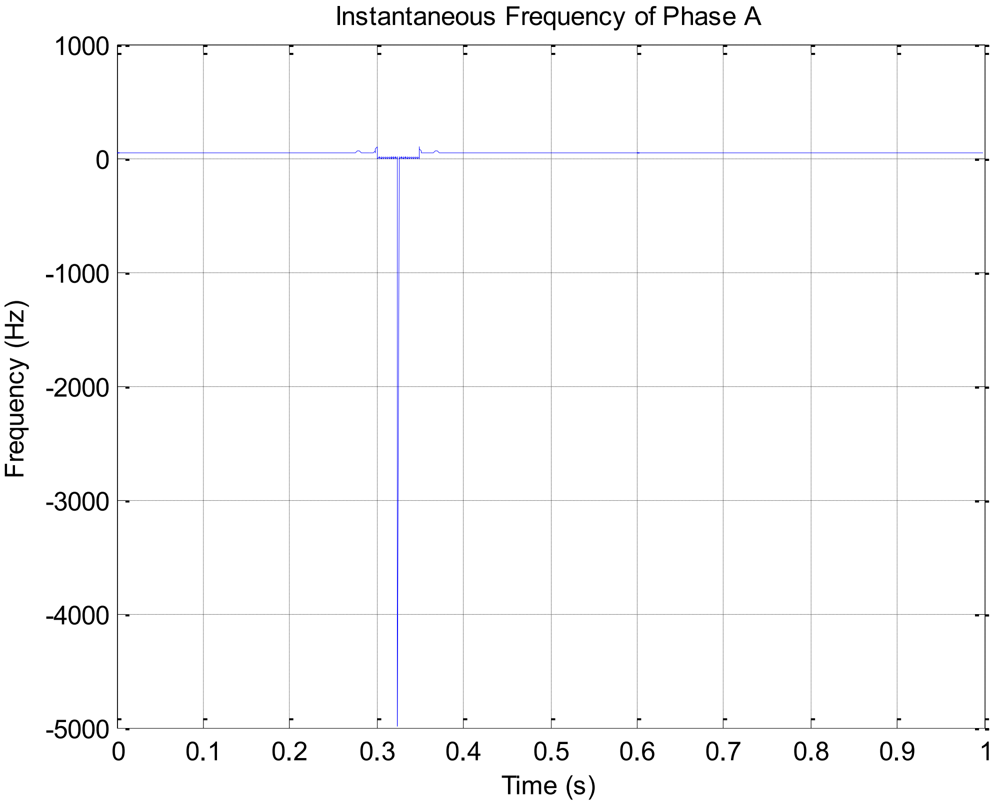

Figure 3

Applications

This simulation is a simplified but powerful tool to:

- Study the impact of electrical faults and islanding,
- Develop and test detection algorithms,
- Understand how different types of disturbances affect voltage waveforms,
- Train machine learning models using labeled synthetic data.

In real-world systems, such techniques are used in:

- **Protection relays** for fault isolation,
- **Islanding detection** in distributed energy systems (e.g., solar microgrids),
- **Power quality monitoring** and **grid synchronization systems**.

Results & Discussion

FFT-Based Analysis

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FFT was applied to voltage signals recorded under normal, fault, and islanding conditions. The spectral plots revealed distinct differences in harmonic content. Fault scenarios showed abrupt increases in high-frequency components, while islanding conditions led to broader spectral spread and reduced dominant frequency peaks. Total Harmonic Distortion (THD) was significantly higher in fault cases compared to the normal condition.

Scenario	**Dominant Frequency (Hz)**	**THD (%)**	**Spectral Width**
Normal	50	**2.1**	**Narrow**
Fault	50 + transient peaks	**17.4**	**Moderate**
Islanding	Drifted near 48–52	**10.6**	**Broad**

Hilbert Transform Analysis

The HT analysis showed that the **envelope** of the voltage signal undergoes noticeable changes during faults—typically a sharp rise in amplitude—followed by oscillatory decay. In islanding scenarios, the envelope showed smoother but prolonged deviations, indicating frequency instability. Instantaneous frequency, derived from the Hilbert phase, further supported these observations, with faults producing rapid shifts and islanding resulting in sustained drift.

Scenario	**Envelope Energy**	**Max Instantaneous Frequency (Hz)**
Normal	Low	~50
Fault	High (spike)	70–90
Islanding	Medium (drift)	47–53

Discussion

The combination of FFT and HT enables a comprehensive view of signal behavior. While FFT captures frequency-domain disturbances effectively, the Hilbert Transform highlights time-domain envelope features that are sensitive to system dynamics. Together, these tools provide strong discriminatory power for identifying and classifying events.

Future Trends

The integration of AI and signal processing techniques is expected to lead to the development of more sophisticated online fault detection systems. This includes the refinement of existing algorithms and the creation of less complex classifiers to improve real-time analysis and response to fault scenarios. Continuous research and development in this area are essential for the advancement of robust power system management and reliability

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Conclusion

This study demonstrates the efficacy of combining Fast Fourier Transform and Hilbert Transform for analyzing power system signal responses to fault and islanding events. This MATLAB script demonstrates how basic simulation and signal analysis techniques can be applied to evaluate a power system's response to critical events like faults and islanding. Both spectral and envelope-based features provide clear distinctions between different types of disturbances. The dual-domain approach enhances the reliability of event detection and holds potential for integration into smart grid monitoring and protection systems. Future work may include real-time implementation and the use of machine learning for automated classification.

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